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Testing Mars Exploration Rover-inspired operational strategies for semi-autonomous rovers on the moon II: The GeoHeuristic operational Strategies Test in Alaska ☆

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ABSTRACT

We used MER-derived semi-autonomous rover science operations strategies to determine best practices suitable for remote semi-autonomous lunar rover geology. Two field teams studied two glacial moraines as analogs for potential ice-bearing lunar regolith. At each site a Rover Team commanded a human rover to execute observations based on common MER sequences; the resulting data were used to identify and characterize targets of interest. A Tiger Team followed the Rover Team using traditional terrestrial field methods, and the results of the two teams were compared. Narrowly defined goals that can be addressed using cm-scale or coarser resolution may be met sufficiently by the operational strategies adapted from MER survey mode. When reconnaissance is the primary goal, the strategies tested are necessary but not sufficient. Further, there may be a set of optimal observations for such narrowly defined, hypothesis-driven science goals, such that collecting further data would result in diminishing returns. We confirm results of previous tests that indicated systematic observations might improve efficiency during strategic planning, and improve science output during data analysis. This strategy does not markedly improve the rate at which a science team can ingest data to feed back into tactical decision-making. Other methods should be tested to separate the strategic and tactical processes, and to build in time for data analysis.

1. Introduction

Successful geologic field work requires adapting field methods to the limitations of the environment to address stated science goals. This is especially true when facing the unique challenges of using semi-autonomous rovers as avatars to conduct field work on remote planetary surfaces, whether that work occurs prior to, following, or in concert with humans on the surface. The Mars Exploration Rovers (MER) mission represents our most extensive experience to date in conducting remote field geology, with over 10 years of robotic exploration as of this writing. Traditional geologic field methods provided the framework used to design operational strategies for the MER rovers during their primary mission [1–3], strategies that were adapted and refined as the needs of the mission evolved [4]. The blueprint for a field methodology for Mars

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Science Laboratory (MSL) Curiosity rover operations was this evolved MER science operations strategy [5]. In like manner, our current work adapts the operational strategies utilized for the MER rovers to determine best practices suitable for designing operations models for semi-autonomous remote geologic exploration of other terrestrial bodies, specifically the Moon.

The Moon presents both benefits and challenges to conducting remote rover-based field geology, including those that are physical in nature (e.g., the properties of the regolith, the lack of atmosphere, the nature of the terrain), those that are based on engineering (e.g., the possibility of near-real-time communications, the wide diurnal variation in temperature) and those related to specific mission architectures (e.g., rovers used prior to, concurrent with, or following human activity [6–8]). Science goals for lunar missions are driven by the Moon's unique geologic history and environment as well. The Moon serves as a potential end-member for several lines of research on small, airless rocky bodies, including identifying and characterizing water ice and other volatiles in the regolith; constraining the thermal evolution of planetary interiors by characterizing surface volcanic deposits and deep interior lithologies; and utilizing cratering history as a basis for relative age dating throughout the solar system [9–12]. Each of these science goals places constraints on the methods and instruments to be used to gather data.

In order to isolate methods of rover-driven field activities from variables introduced in utilizing rover-associated hardware and instruments for this work, we avoid the common strategy for rover analog field tests, the use of a rover mock-up armed with a suite of instruments, with an engineering or "astronaut" team in the field and a "blind" science team offsite (e.g., [6–8,13–20]). Instead, we conduct field work using commercial instruments that provide similar information as flight-ready instruments, and utilize humans for mobility. Examining only the field strategies that scientists have developed around using a rover requires no specialized equipment to be functionally similar to rover work, and allowed us to isolate for testing the science-driven protocols in the decisional path, rather than those protocols driven by engineering requirements.

In previous GeoHeuristic Operational Strategies Test (GHOST) field work, we examined how well MER-informed operational strategies performed at a terrestrial site analogous to the lunar South Pole-Aitken basin in the broad range of volcanic materials present, and its potential presence of lower crust/upper mantle samples [21]. Here, we examine a different lunar geologic paradigm: searching for ice in a regolith. We conducted field tests at two glacial moraines as analogs for a potential ice-bearing lunar regolith. Two testable hypotheses were defined: (1) the science methodology utilized in MER operations is sufficient to locate, identify and characterize important geologic materials, specifically water ice; and (2) regolith-like material (an amalgamation of poorly-sorted and lithologically diverse rocks and soil fragments sourced and transported from local and surrounding regions) can be used to coarsely reconstruct a region's geology using MER-derived rover strategies.

2. Choosing the ice analog

The nature of the analog site is an important constraint for assessing appropriate operational strategy. For this investigation, glacial moraine environments were chosen to be roughly analogous to ice-bearing lunar regolith as the clastic materials in both environments were pulverized and transported unsorted from surrounding and underlying terrain. Of particular importance, yet undetermined for the lunar environment is what form water ice, if it is present, might take in the regolith. Although lunar samples returned by the Apollo missions were found to be entirely composed of anhydrous minerals [22], later investigations suggested that the deep lunar interior may contain more volatiles than previously estimated [23–25] and that water ice may be present and stable on the surface [26–33]. However, modeling based on neutron spectroscopy aboard Lunar Prospector argues that the upper 5–20 cm of polar regolith is dry, and that hydrogen is concentrated in the subsurface [34,35]. This suggests that water ice, if it exists, may be disseminated and mixed with soil in permanently-shadowed craters. We therefore assume an analog of standalone subsurface water ice exists within an unconsolidated regolith and are able to set up robust test parameters with a suitable analog. As subsurface ice exists on other planets, conducting a test under these conditions also will have broader implications than one focused on a specific potential manifestation of lunar subsurface ice.

We chose Gulkana and Matanuska glacial moraines in central Alaska (Fig. 1) as analogs ice-bearing glacial moraines because they (a) have little encroachment by vegetation; (b) are associated with active glaciers; and (c) were formed by glaciers that sampled a wide variety of geologic materials upstream. This last issue was particularly important to test whether the methodology could yield appropriate and sufficient information to hypothesize a reasonable potential lithology of several source regions, rather than a lithologically homogeneous set of fragments leading to a single source. For the purposes of this test, the mechanical properties of the ice-bearing regolith analog were considered more important than whether its geochemical composition was analogous to lunar regolith.

3. Field sites

3.1. Gulkana

Gulkana Glacier in the eastern Alaskan Range, 12 km east of the Richardson Highway and 200 km southeast of Fairbanks, Alaska is ~9 km long and its areal extent was 16.7 km^2 as of 2001 [36,37]. The fieldwork for this study took place in the proglacial outwash south of the glacier's terminus, where braided streams and mass wasting of the valley walls have reworked and modified the terminal moraine.

The main body of Gulkana glacier rests on bedrock dominated by Cretaceous granitoids, mostly granodiorite and quartz monzonite. These have local propylitic alteration, with secondary epidote + carbonate ± pyrite. Some propylitic alteration overprints earlier acidic alteration

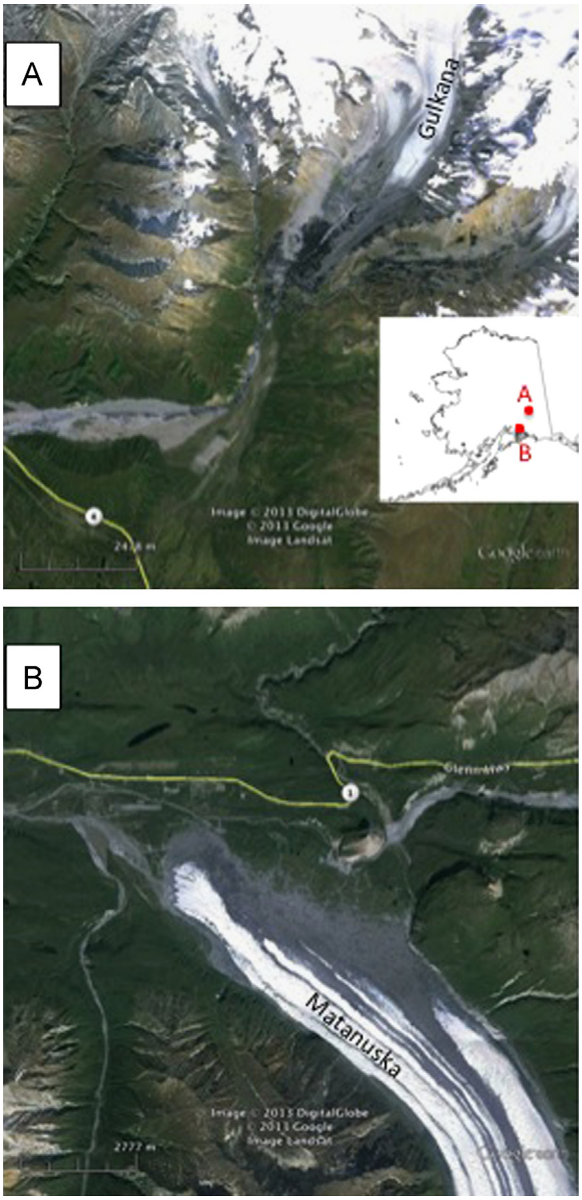

Fig. 1. Google Earth Landsat images of (A) Gulkana (foot: 63°15′11″N, 145°23′50″W) and (B) Matanuska glaciers (foot: 61°46′40″N, 147°45′45″ W). Inset map of Alaska shows locations.

indicated by vuggy quartz veins. The walls of the glacial valley are largely made up of the Pennsylvanian-Permian Tetelna Volcanic Complex [38]. These are shallow marine andesitic and dacitic pyroclastic and volcaniclastic deposits with minor lava flows and sedimentary layers. Adjacent to the glacier's foot and outwash plain, the Tetelna is exposed where streams cut through the till – here it is pervasively chloritized and locally silicified. A variety of other sedimentary and intrusive rocks have also been mapped in the region [38,39].

An initial survey of the valley prior to the field work revealed that the valley contains several lithologies that do not closely match any mapped and described units in the immediate vicinity of the glacier, but which are relatively unweathered and generally angular, consistent with their being locally derived. These include clinopyroxenite, serpentinite, and massive epidote-quartz-carbonate rocks that all are found as >1 m boulders. The Denali fault, a major right-lateral structural feature, lies just north of the glacier's head and associated faulting likely contributed to the complex mixture of lithologies observed.

3.2. Matanuska

The Matanuska glacier is one of the largest glaciers extending from the Chugach Mountain ice fields and has a catchment of $\sim$650 km^2 and length of >45 km [40]. Fieldwork occurred in the hummocky area near the modern terminus, amid till-covered stranded glacial ice. The bedrock geology of the Matanuska glacier is a product of long-lasting northward subduction and accretion followed by right-lateral faulting [41]. The head of the glacier lies in the tectonically complex Chugach Terrane, which is a mélange of poly-metamorphosed flysch and mafic volcaniclastics [42]. The glacier's foot and the last 12–13 km of its length lie north of the Border Ranges fault in the Peninsular Terrane, a poly-deformed and metamorphosed Triassic–Jurassic oceanic arc sequence with intercalated Cretaceous marine sediments [43]. These sequences are locally (and in the vicinity of the glacier) near Jurassic–Triassic gabbroic plutons and Tertiary hypabyssal felsic and intermediate stocks [41].

4. Methodology

In terrestrial field work, decisions are continually made that affect data collection and analysis, and thus the science return. Decisional pathways are commonly less formalized or quantifiable in traditional terrestrial field work than in planning and executing rover operations, but the decisions to be made are similar. These include: (1) where to collect data; (2) which tools to use; (3) which data to collect based on continuous iteration of the data in hand; and (4) how much data is sufficient to address the hypotheses driving the field work. We modeled our field campaign around decisional points encountered regularly during MER rover science operations planning. We define the tactical process as immediate decisions regarding the choice of rover and instrument commands, whereas the strategic process refers to decisions regarding longer-term rover observation strategies. When and how these decisions occur, and how they influence each other is up to the team conducting the observations.

4.1. Team organization and observational structure

4.1.1. MER science team and planning structure

MER science operations are driven by the Science Operations Working Group, or SOWG. The SOWG determines the content of the science activity plan for the sol being planned, and consists of individuals responsible for the health, safety and sequencing of the science instruments (tactical Payload Uplink and Downlink Leads), individuals who guide and record the tactical process (the SOWG Chair, Documentarian and Keeper of the Plan)

Table 1
MER and analogous GHOST operational roles and instruments.

MER		GHOST
Roles		
Mars Exploration Rover: Robot that performs activities, transmits data to Instrument PDL	→	*GHOST Rover:* Person who follows commands and then brings instrument data (i.e., images or spectral data) to the Science team.
MER SOWG: Group that tactically determines the content of the science activity plan for the sol being planned, and includes the SOWG Chair, Documentarian, Keeper of the Plan, Instrument PDLs and PULs	→	*Science Team:* Two people who analyze data received, briefly discuss, then tell the rover what to do next
Long-term planner: Provides strategic guidance	→	Strategic guidance discussed by Science Team ahead of campaign.
Instruments		
Cameras	→	*SLR Digital Camera:* at a range of scales
• Navcams – 0.77 mrad/pixel angular resolution, 45° × 45° field-of-view navigational cameras		
• Hazcams – 2.2 mrad/pixel angular resolution, 180° field-of-view hazard avoidance cameras		
• Pancam – 13-filter, UV–vis 0.28 mrad/pixel stereo panoramic camera [45]	→	• Images taken from infinity to about 1.5 m distance
• Monocolor arm-mounted Microscopic Imager (MI [46])	→	• Images taken at ~15 cm allowed 24 × 36 mm^2 images at ~10 μm/pixel
Analytical instruments		*Analytical instrument:*
• Pancam: 13-filter multispectral imaging	→	• Portable multiband photometer - measures separate, non-overlapping ranges of wavelength centered on 470, 525, 560, 585, 635, 660, 700, 735, 810, 880 and 940 nm
• Miniature Thermal Emission Spectrometer (MTES) [47] – provide mineralogical and thermophysical data on surface materials		
• Mössbauer Spectrometer (MB) [48] – Fe mineralogy		
• Alpha Particle X-Ray Spectrometer (APXS) [49] – minor and major elemental composition		

and the strategic process (the Long-Term Planner), and other team members who analyze downlink data and suggest tactical observations, as well as perform science analysis offline from the tactical process. MER roles pertinent to this field test are shown in Table 1, compared to the analogous roles of the GHOST team members.

Each planning period, the SOWG chooses activities to be executed by the rover and instruments, based on the overall mission science goals, the objectives for the current location, and environmental and engineering constraints. Common decision points for the SOWG include determining targets, which instruments to use, and when sufficient data has been collected so that the rover can move on. A typical sol plan may include a drive to a target of interest, acquiring a panoramic mosaic of a location, or deploying and acquiring data using contact instruments. An overall plan for a science objective (e.g. characterize the Home Plate feature at the Spirit landing site and determine the process that formed it) would encompass multiple sols of varying types of observations, and would be planned on the strategic timeline.

4.1.2. GHOST 2 field test science team and planning structure

The field team was divided into a two-person Rover Team, a two-person Tiger Team, a field site expert, and a field assistant. The Rover Team (Table 1) determined the observational strategies based on common MER observational sequences, which were then executed by a human "rover" field assistant, equipped with off the shelf commercial instruments. The observations are outlined in Tables 2 and 3 in the supplemental material. The Rover Team limited their analysis to the data acquired by the "rover" itself, rather than any information they could gather from looking around. They analyzed data and collected data that informed their decisions on a simulated tactical timeline.

The Tiger Team reconnoitered each site using traditional terrestrial field methods. The objective of the Tiger Team was to provide a standard of results derived using terrestrial methods for comparison to the results of the Rover Team derived from MER-informed operational strategies alone. Because the moraines are an admixture of materials sourced from the entire surroundings, lithology was somewhat independent of location on the scale of tens of meter. It was therefore decided that the Tiger Team did not need to precisely follow the traverse of the Rover Team, as had been done in previous work [21], because the lithologies would be similar regardless of traverse. This choice also avoided any inadvertent "cross-pollination" of ideas or concepts between teams. Identifying locations of potential permafrost, however, was seen to be location-dependent, so the Tiger Team did retrace that portion of the rover traverse. Additionally, to avoid bias introduced by the varying expertise of each participant, the members of each team were changed between the Gulkana and Matanuska sites. Because of the nature of human observations, this analysis extrapolates from notes the Tiger Team observations the approximate equivalent set of images and other data acquired by a rover instrument (Tables 2 and 3).

The field site expert, not part of the Rover or Tiger Teams, reconnoitered locations prior to fieldwork and accompanied the Rover and Tiger Teams to the field, but did not participate in data analysis or interpretation. This person was therefore familiar with the both local geology and the way each team conducted their field work, but could not influence either team.

4.2. Instruments

The MER rovers are equipped with an instrument suite designed to acquire data that mimics the basic field tools of a geologist (eyes, hands, and hand-lens; Table 1). Additionally, MER improves on these basic observational tools through the use of geochemical instruments that would commonly be employed in a laboratory, rather than a field setting for determining elemental composition, mineralogy, and characterizing thermophysical properties of surface materials. Together (Table 1), these tools represent a generalized set of instruments that would likely be used on a reconnaissance rover in a lunar environment. The instruments can be categorized as remote or contact instruments, and with respect to the types of data they provide on surface materials: navigational, physical, geomorphologic or geochemical information.

Using MER as the template, we took images simulating the range of resolutions represented by the cameras on MER. Images taken from infinity to about 1.5 m distance mimicked the range of resolutions available with mast-mounted cameras such as Pancam and Mastcam [1,45]. A working distance from the front of the lens to the target of $\sim$15 cm allowed 24×36 mm^2 images at $\sim$10 μm/pixel to be taken using ambient light; these parameters are within the range of the MSL MArs HandLens Imager (MAHLI) [50]. To mimic the acquisition of basic mineralogical data, we utilized a portable multiband photometer that is sensitive to many Fe-bearing species. No effort was made to mimic geochemical "contact science" instruments because these would have been impractical to wield with the small field crew.

4.3. Acquiring observations

At each site, observational "days" were divided into a detailed data acquisition plan for targets of interest. In the previous field test [21], we defined a "traverse methodology" that was based on MER campaigns, in which the primary objective was to drive to another location and secondarily to acquire targets of interest along the way. We also defined a "survey mode" based on historical MER activities where the science objective was to make a detailed assessment of a feature, target or location (e.g. reconnaissance of the Burns formation and Cape York by the Opportunity rover [51–53]); thus, the number and frequency of observations is higher and more systematic. This is the mode we utilized.

When MER is in "survey mode," a set of panoramic images is commonly acquired before (and sometimes after) target analysis. Each target is imaged at outcrop-scale and at an appropriate scale (using one or more color or spectral filters [44]) to place the feature of interest into geologic context. Targets within each contextual image are then chosen based on science goals, and examined by one or more of the contact science instruments; the choice of which instruments are used is constrained by power, data rate and data volume. The number of observations acquired in this mode is typically greater than that acquired during study of a target in traverse mode, because a primary goal is to place the target into the context of the larger feature of interest. On Mars, this has translated to acquisition of 5–10 observations per "Station" or target, with 5–15 Stations to fully characterize the feature of interest. Decisional points are reached at the conclusion of each Station.

4.3.1. MER survey mode adapted to the GHOST 2 field test

For this test, we provided all team members with "orbital" images of both field sites (acquired from Google Earth). These images were 1:5000 resolution and in color. From these images, we determined the strategic objectives and a notional science plan.

On the ground at each site, we utilized the following GHOST protocol (Fig. 2): (1) acquire 360° of panoramic pre-approach images and from these, determine a preliminary assessment of geologic history and identify locations most likely to contain subsurface water ice; (2) plan a traverse with specific stops for data acquisition, where the traverse and Stations chosen serve to address the hypotheses of the test; (3) at each Station, acquire m-scale images of sites and from these choose up to five targets that potentially best represent materials of interest; (4) acquire images of selected targets at cm-scale resolution and then at 10 μm/pixel; (5) sample targets for offsite "laboratory" compositional analysis. Steps 3–5 were followed for each site selected in step 2. Additionally, we chose to conduct

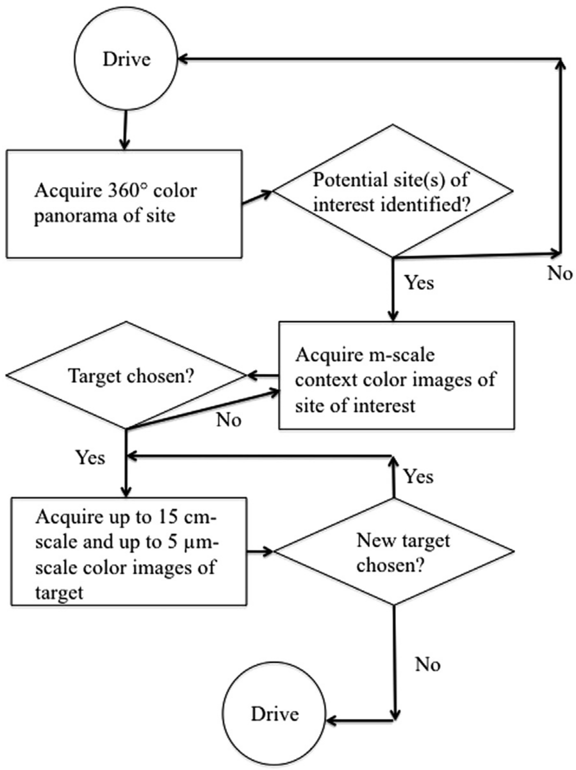

Fig. 2. Generalized data acquisition strategy for the Rover Team. Rectangles represent data acquisition points, diamonds represent decisional points, and circles represent mobility. The decisional path is based on [1] and adapted from MER operational strategies and previous field tests as reported by Glass et al. [13].

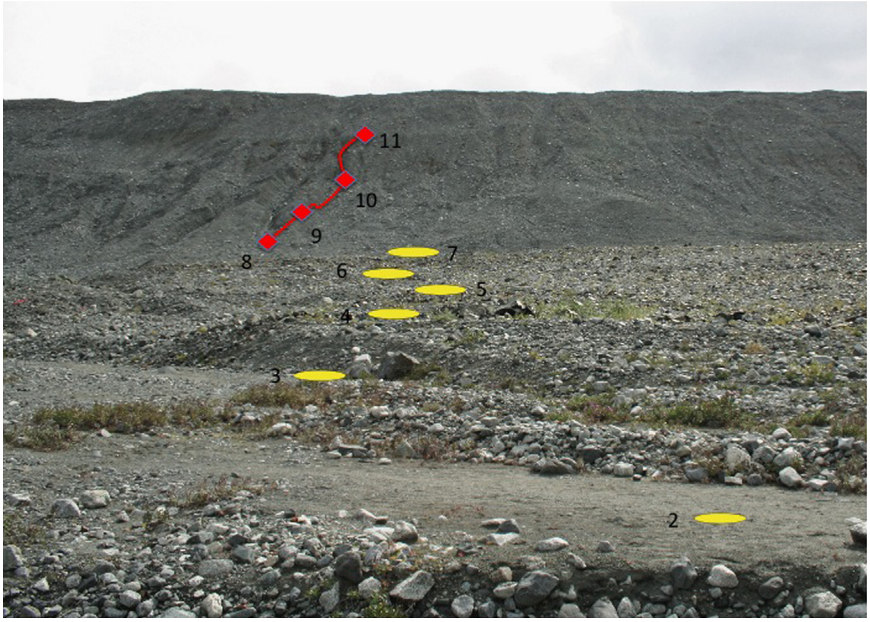

Fig. 3. Rover traverse planned on the first day of operations by the Rover Team, based on data from the 360° panorama and Station 1, Gulkana Glacier site. Stations where observations were taken are shown as yellow ovals. The autonomous navigation path executed on the second day of operations is indicated in red, with red diamonds indicating observation Stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

MER-derived operational strategies in near real-time to mimic a likely lunar mission scenario.

5. Observations and interpretations

5.1. Gulkana Rover Team observations

The Rover Team set up a Base Camp from which to plan observational strategies, sketched the overall geologic setting of the site and then commanded the rover to acquire a 360° panoramic mosaic that covered the site from approximately 30° above the horizon to the base of the rover. The Rover Team identified a discrete layer half a meter thick, approximately 2–5 m from the top of the southern moraine. The layer was darker than those above and below it, was continuous for a distance of several tens of m, and appeared by morphology to be more resistant than those layers above and below it. The bottom of this layer appeared to be the source point of several gullies. Based on these observations, the Rover Team identified this layer as the most likely candidate for subsurface water ice within the reachability of the rover.

The Rover Team planned a traverse to address the two goals of identifying and characterizing a potential outcrop of subsurface ice, and characterizing the lithologic diversity of the regolith analog (the traverse is shown in Fig. 3). The traverse advanced up section from the floor of the glacial valley to the bottom of the more resistant layer in the southern moraine ridge. Acquired data were downloaded onto a laptop at Base Camp and analyzed by the Rover Team, to determine whether changes in the original traverse were warranted. Observations were planned at regular intervals so that the climb could be utilized to sample lithologic diversity as a function of upslope position. Because the extreme diversity of represented lithologies was evident in the first panorama, the Rover Team made the decision almost immediately to focus their efforts on acquiring the most comprehensive dataset possible, rather than trying to analyze each image or spectrum in a more than cursory way. Additionally, because of the difficulty in determining a full inventory of this high diversity, the Rover Team adopted a plan in which a lithology survey mosaic (a three-image mosaic at mm-scale, downlooking) was regularly taken at each station to capture as much as possible the lithologic diversity present, and to support correlation of observed lithologic diversity to vertical distance upslope.

For the traverse up the steep unconsolidated slope, the Rover Team judged it impractical to have the rover physically return to Base Camp after each station for data "downlink". Consequently, the Rover Team pre-planned a traverse and series of observations analogous to an autonomous navigation sequence, or "blind drive." This traverse started at Station 8, the base of a gully 3–4 m wide, running E–W from the base of the candidate ice-bearing layer to the base of the moraine (Fig. 3). From this point, and at every 10–15 m, the rover acquired a nine-image lithology survey mosaic, and a three-image 120° mm-scale mosaic upslope for traverse assessment. This translated to three separate Stations based on the rover's assessment of a safe position from which to stop and take images. At the terminal station (Station 11), where the bottom of the candidate ice-bearing layer contacted the unconsolidated material in a gully, the rover also acquired a suite of images of the location showing meltwater flowing out of the ice-bearing layer. This Station is shown in Fig. 4.

Fig. 4. Gulkana Glacier Station 11, near the top of the moraine. Loose cobbles and pebbles of varying lithologies are embedded in a coarse-sand and gravel matrix. The image shows meltwater flowing out of the ice-bearing layer.

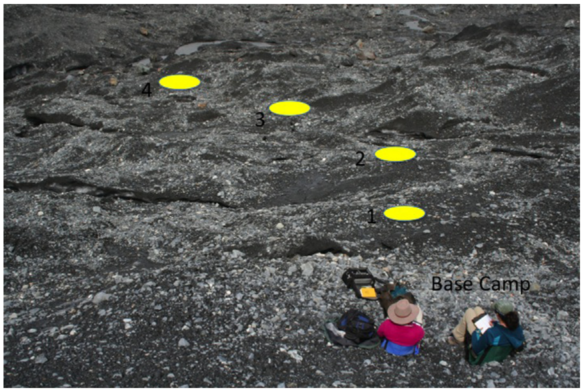

Fig. 5. Rover traverse planned on the second day of operations by the Rover Team, based on data from the 360° panorama, Matanuska Glacier site. Stations where observations were taken are shown in yellow; the four boulders that constitute Stations 5–8 are over 25 m away and are not shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.2. Gulkana Tiger Team observations

The Tiger Team began operations by climbing to a high point on the southern ridge (moraine), sketching the landscape, and using observations from this point to make a first-order characterization of major local lithologies. They then moved to a terrace of angular rocks within the stream-bed, approximately 15 m from Station 1. From this position the team observed the grain size distribution of clasts within and outside the channel.

The team determined that the lithologies recorded up to Station 1 represented the majority of the fragments at the site that were pebble-sized or larger. Thus, after this point, the team focused on identifying and characterizing the range of lithologies represented in the coarse unconsolidated outwash sediments as they moved from station to station. Because Stations 3 and 4 were only 10 m apart, the Tiger Team made observations and took samples of both Stations concurrently. The team then hiked up to the top of the southern moraine, taking observations at Stations 6 and 7 along the way. Finally, the Tiger team explored the entire autonomous navigation traverse of the rover without specifically dividing it into Stations. They ended their run by moving from the traverse path to examine exposed bedrock in the gulley (missed by the Rover Team due to the nature of blind driving).

5.3. Matanuska Rover Team observations

At Matanuska, ground ice was pervasive throughout the site; thus, addressing the first hypothesis of this test was impractical and the Rover team chose to test the second hypothesis only.

First-order observations indicated less lithologic diversity at this moraine than at Gulkana, but the diversity was still high and the Rover Team enacted their plan of systematic observations as tested at Gulkana, with the first Stations being very close (~5 m apart, as shown in Fig. 5) to document lithologies without respect to position, and the subsequent Stations being further apart, to determine lithologic diversity as a function of distance from the glacier. Three-image mosaics were taken along each short traverse to document context and provide additional data that could be reviewed when not conducting tactical operations. These were then followed by a single image for context and a nine-image mosaic of the surface at each station at the mm-scale. These data (e.g., Fig. 6) were used to choose targets of interest for imaging at μm-scale resolution.

Once a survey of local lithologies was completed, the Rover Team planned a “long drive” traverse out to a boulder field several tens of meters to the south, with the rationale that the boulders could be used as proxies for remnants of outcrop eroded by glacial movement. The rover then acquired images of four boulders (Stations 5–8). Each boulder was captured in a single image (cm-scale), then in a three-image mosaic at mm-scale resolution, and finally in a series of μm-scale resolution images (this sequence is shown in Fig. 7). Between each of the boulder Stations, the rover acquired a three-image mosaic in the direction of the next station.

5.4. Matanuska Tiger Team observations

The Tiger Team began operations by climbing to a high point and sketching the landscape. They then conducted a brief reconnaissance of unconsolidated moraine fragments and identified several major lithologies. The Tiger Team chose to examine the boulder field as proxies for outcrop, skipping Stations 1–4 and visiting only Stations 5–8. On the way to the boulder field the Tiger team took several samples of representative lithologies. The Tiger Team did a visual inspection of the boulders in Stations 5–8, including breaking off fresh samples (something the Rover Team was not allowed to do).

6. Discussion and lessons learned

6.1. Hypothesis one

The operational strategies and modest instrumentation utilized provided the Rover Team with adequate information

Fig. 6. Sequence of context and nested images for Station 2, Matanuska Glacier, shown as an example of the lithology survey. Three context images (a) were taken along traverse, followed by a nine-image mosaic. (b) From these data, six individual clasts were selected for imaging at μm-scale.

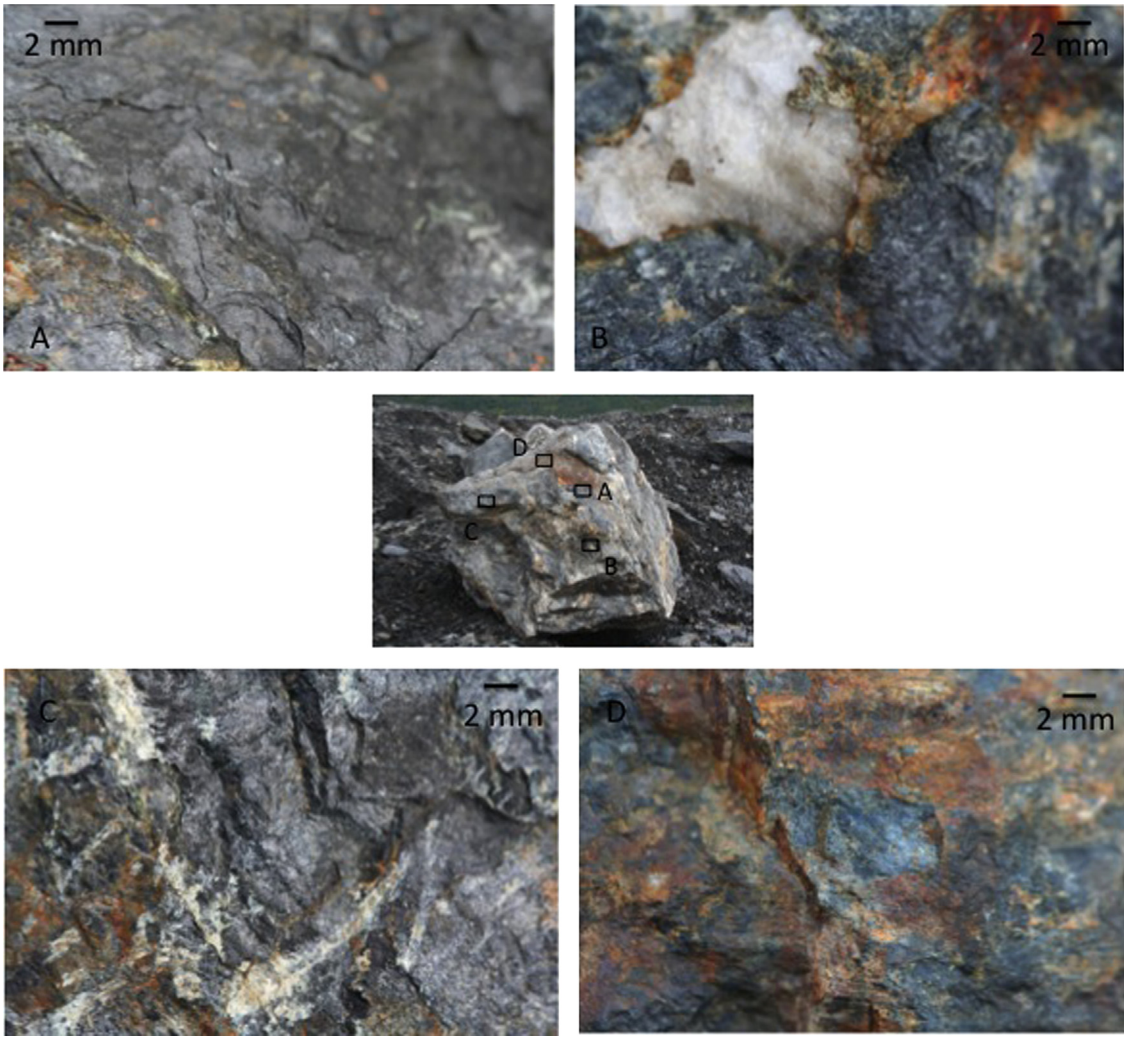

Fig. 7. Station 5, Matanuska Glacier. One context image (center) and a representative subset of the 6 μm-scale images (a–d) are shown. The 1.3 m diameter boulder shown in these images was interpreted to be a schist by the Rover Team, and a slate by the Tiger Team.

for them to identify ice and liquid water at their primary target, and collect sufficient appropriate data to characterize the contextual geology (approximate thickness, morphology and mineralogy of constituents in the ice-bearing layer). Hypothesis one was thus confirmed. This is because during survey mode, there is a specific, narrow goal to be addressed and in this mode (1) resources are concentrated, rather than divided between many competing goals; and (2) time is less constrained by the pressure to move on to the next site. Using this mode, the Rover Team was therefore able to focus resources on only four tasks in addressing hypothesis one: (1) search for geologic evidence of subsurface ice; (2) identify

potential targets for ice; (3) rank the targets according to strength of evidence; and (4) examine each one in turn. This test also revealed an underlying assumption of survey mode: for high-priority targets on Mars (e.g. outcrops revealing significant stratigraphy; features such as Home Plate), the constraints of time, data rate and volume did not apply in the normal tactical sense. They were considered variables only for each individual sol, rather than over the period of the investigation; the rover remained at each target until consensus was reached among the team members that collecting further data would result in diminishing returns. Survey mode was thus essentially driven by the strategic timeline rather than the tactical one. We believe this stemmed from the fact that targets examined in survey mode were chosen on the basis of their salience to a well-defined hypothesis to be tested directly. Survey mode is by itself an insufficient strategy to address broad or general objectives, such as a common mission goal to "characterize the geology of a site." It is not clear whether these operational strategies would be sufficient if the goal was less straightforward (e.g., where multiple features must be identified, contextualized and characterized, or where the feature or material of interest is below the resolution of reconnaissance images, or if the site contained heterogeneous surface expressions of the material or feature of interest).

As expected in selecting the field sites, clues to the presence of subsurface ice could be identified in the site's macromorphology, with cm-scale resolution. For a scenario in which the overarching goal is narrow but requires identification and interpretation of features or materials below the resolution of these reconnaissance images (e.g., where identification requires discrimination of different lithologies), we recommend that a combination of survey mode and a similar observational sequence such as the lithology survey be employed. Such a scenario is described in the next section.

6.2. *Hypothesis two*

The teams were able to identify several major lithologies represented in the two analog lunar regolith environments studied. However, the Rover Team could only determine the geologic regimes in a very basic sense and the regional geology remained mostly unknown. Thus hypothesis two was only partly confirmed.

6.2.1. *Characterizing the diversity of represented lithologies*

The diversity of lithologies posed a significant challenge for both teams, especially at Gulkana Glacier. For the Rover Team this necessitated a conscious tradeoff between resolution sufficient to reveal lithology and coverage of the macroscale diversity of the regolith. Determining rock lithology requires sufficient resolution to identify grain size, morphology and appearance, color, crystal form, cleavage, and unique mineral shapes. For this field test, we determined a threshold resolution of about 0.1–0.3 mm/pixel to be able to discern these characteristics, and utilized the lithology survey to acquire sufficient images to identify a reasonable subset of the lithologies present. We thus adopted the regular lithology surveys described in Section 5.1, as recommended in Yingst et al. [21], to acquire a dataset intended for analysis outside of the tactical timeline. However, these surveys provided the Rover Team with images that were at a resolution essentially $2\times$ the resolution of the highest Pancam image available (0.4 mm/pixel from a 70° downlook [47]), and equal to some of the highest the resolution achieved by the MSL M100 Mastcam camera for the systematic clast survey campaign (0.21 mm/pixel from a -45° elevation downlook [54]). This resolution used can only be acquired in the current MER or MSL instrument suite by utilizing the arm-mounted MI or MAHLI respectively.

This is a crucial point, because achieving a similar level of understanding on Mars with a MER- or MSL-type instrument suite would require taking one or more sols to deploy the MI/MAHLI. For example, the rover Opportunity examined Whitewater Lake, light-toned material at an outcrop informally named Matijevic Hill, that may contain clay minerals, a crucial new discovery on Mars. Whitewater Lake outcrops appear interspersed with more resistant units, such as Kirkwood – which contains small spheres with composition, structure and distribution that differ from other iron-rich spherules, nicknamed blueberries [55]. The presence or absence of these spherules became critically important as a potential lithomarker in tracing outcrops across Matijevic Hill. However, given the very small size of the spherules (1 mm), the team struggled to discern whether a given outcrop had spherules or not using only Pancam images. From farther than ~2–3 m away, it was impossible. The only way to definitively determine the presence, abundance, and character of the Matijevic Hill spherules was to deploy the Microscopic Imager on the robotic arm, an activity requiring an extra planning sol to position the rover, plus a mission decision to use the arm, which has lost several motor windings and is considered a consumable resource. In short, the science operations scenario had to be significantly modified to allow for full characterization of key decisional targets.

Our adaptation of the methodology was thus a significant departure from nominal MER operations, but we utilized it to successfully make a coarse assessment of the lithologic diversity. One lesson learned from this study, then, is to consider mission operations scenarios or architectures that would increase the amount of lithologic or textural scale data that can be returned from a semi-autonomous rover mission. With a MER-type architecture and instrument suite, this could be accomplished through employing a regular cadence of short drives (5 m or less) ending in downlooking (high-resolution) imaging, or executing longer drives with several planned mid-drive MI images acquired regularly. Such a scenario would trade mobility and amount of ground traversed for lithologic information. Alternately, the rover instrument suite could be altered to include a devoted mast-mounted camera or lens that can acquire higher (mm-scale) resolution images from a distance, so images revealing lithology could be acquired at a similar cadence as panoramic or targeting images are currently acquired from the MER and MSL mast-mounted cameras. In this case, the trade would be between lithologic information, and power and data volume.

An unintended consequence of this adaptation was that the Rover Team sacrificed context for sampling as much diversity as possible. The issue of how to capture maximum diversity was exacerbated by the lack of locational awareness, which can be divided into lack of a three-dimensional perspective (i.e. different angles and views [55]) and lack of a sense of scale [56]. These factors slowed down tactical analysis, and even negatively influenced imaging choices. For example, one of the most common geologic field techniques is to examine first the location with the greatest expanse of in situ rock, because it provides the largest amount of real estate in the context of its emplacement. On Earth, this usually means outcrop, but in a remote planetary environment, outcrops are often rare and difficult to access. In such cases, boulders can be used as stand-ins, as they contain minerals within a whole rock context, and can sometimes represent large fragments of outcrop. While boulders were available to the Rover Team at both sites, they were prioritized lower because the team did not intuitively grasp the perspective and the scale of these boulders on the tactical timeline, and thus their ability to assist in contextualizing the lithologies. Introducing a scale bar or object embedded in images as part of a toolkit would provide a rapid, intuitive scale perspective into every image.

6.2.2. *Strategic analysis versus tactical decision-making*

As in previous field tests [21], the amount of time the Rover Team spent planning observations lessened the time available to analyze acquired data, and thus decreased the tactical usefulness of that data. In the case of this test, however, even with more time made available for analysis, and even with the knowledge that the rover could spend essentially unlimited time at each station, Rover Team members focused on planning and executing imaging sequences, rather than conducting more in-depth analysis during down-times and potentially using that information to drive science observations.

Although the addition of systematic data collection did provide the Rover Team with a more complete picture of the overall geology, examining and properly documenting those images for future reference took a great deal of time and focus because of the difficulty of moving back and forth from the tactical to the strategic thought process. The Rover Team thus made the assumption that the data would be mined later (on the strategic, rather than the tactical timeline) for more detailed information, and focused instead on collecting and documenting as comprehensive and robust a dataset as possible. Many mm-scale (handlens-type) images recorded key petrologic features that would have allowed the Rover Team to create more cogent hypotheses regarding lithology (and may have informed the tactical process) if the team had analyzed more of them on the tactical timeline.

Conducting strategic science in parallel with tactical work is common in the MER paradigm; part of the science team shepherds the tactical process for the next martian sol, while other team members simultaneously analyze the non-decisional (i.e., not crucial for making decisions for planning the next sol) data from the last sol for strategic planning of future sols. Indeed, in the case of MSL, this model has been adapted to include even greater separation between the tactical and strategic science processes. For this field test, however, a more likely lunar paradigm was used: that of real-time data return. The consequence of this rate of data flow was that, for the data to have any possibility of informing the tactical process, data analysis had to occur essentially at the same time as data acquisition. One lesson learned in this case is that MER-inspired methodology is not a fully effective model for maximizing science return for a mission architecture that allows for real-time data return.

Our results strongly agree with those of previous analog tests [21,57,58] and in situ rover field work [2]: robust science input at all stages during the tactical process is critical to ensure that science goals are met. The questions that follow from this lesson learned, then, are: (1) Is focusing solely or primarily on tactical data-gathering the most effective use of the science team? (2) If not, what changes can be made to science observational choices that will support both tactical and strategic decision-making and analysis in real time? One possible refinement of future tests would be to include additional Rover Team members, tasked specifically with data analysis during the field test (analogous to the MER Payload Downlink Leads, except that their work would be conducted concurrently with the tactical process to accommodate the more rapid lunar timeline). This strategy could run the tactical and strategic timelines in parallel, with some avenue needed for the strategic team to be able to interrupt the tactical process if the situation warrants, or in shifts sequentially with the tactical planning, such as was tested during several Desert-RATS tests [57,58]. We also note that pauses already occur in the tactical timeline due to engineering constraints (e.g., dust cover on solar panels requiring greater time to recharge batteries, unforeseen anomalies, recharge of batteries) or for use of instruments requiring time to acquire data (e.g., a Mössbauer spectrometer) that would slow down the tactical timeline, even in real- or near-realtime operations. These times could be used to do analysis and would be possible places for a strategic team to work while giving the tactical team a mental break.

6.2.3. *Environmental and test-specific limitations*

Human response to the environment was a factor in the tactical decision process, especially in pursuing hypothesis two. In the case of the Rover Team in particular, the cold temperatures and the necessity of remaining in one place (Base Camp) throughout the test combined to cause fatigue. Both teams noted their fatigue, and both teams recorded the qualitative assessment that it affected their efficiency increasingly as time passed. Although it is expected that any lunar science team would be housed in environmentally controlled conditions (lessening physical fatigue), the amount of data received on the tactical timeline will likely be much greater, and transmission of that data much more rapid than for MER (increasing mental fatigue). This human factor may thus significantly affect science return [56]. Though it was not possible to test within the limitations of this analog experiment, a lesson learned for lunar fieldwork is to ensure that science team members are given sufficient breaks and are cycled through operations in shifts [2,57,58].

7. Conclusions

The GHOST field experiments are designed to focus on identifying, outlining and organizing our understanding of how MER-heritage, science-driven rover operational strategies affect science return in a lunar environment. The results are thus qualitative judgments regarding a process rather than a quantifiable set of criteria that, if met, will produce a predicted set of deliverables. Results of this fieldwork indicate that for lunar semi-autonomous rover missions where the science goal is general, such as characterizing a regolith, the strategies as tested here are necessary but not sufficient. If, however, the goal is narrowly defined and can be addressed using primarily cm-scale or coarser resolution (as acquiring higher resolution images on numerous targets is not possible in the current rover configuration), the operational strategies adapted from MER survey mode may be sufficient, given the caveats noted here. Further, we note that there may be a set of optimal observations for such narrowly defined, hypothesis-driven science goals, such that collecting further data would result in diminishing returns.

For more general goals, adding systematic observations (as recommended by previous GHOST tests) provides a better dataset for strategic planning and data analysis, but does not improve data ingestion by the science team rapidly to inform the tactical process. Other methods of separating the strategic and tactical processes, and providing time for science analysis to progress, should be tested. An additional important issue is to understand how and how much discovery is impeded when incoming data are not processed quickly enough to inform the tactical process.

It is important to recognize that different types of goals may require different (and potentially mutually exclusive) operations strategies. We have determined that survey mode, adapted for lunar use, would be a reasonable starting point for science operations when the goal is to identify a single feature, unit or material. In future work we will widen this test of the survey mode to determine the important parameters that would make it most successful in maximizing science return within the constraints of a broader variety of goals.

This work demonstrates explicitly that where the site lithology is heterogeneous, characterizing that lithology (as opposed to morphology and shape of rocks or macrofeatures) would require planning more frequent drives, deploying the rover arm instruments far more frequently than current operations allow, or being able to acquire resolutions of 0.1–0.3 mm/pixel from a distance. The most operationally simple and efficient way to acquire images at fine enough resolution to characterize lithology would be to include in a rover payload a dedicated mast- or body-mounted camera that can acquire images of 0.1–0.3 mm/pixel at a distance of at least 2–5 m away (the distance at which the majority of contact science targets are identified for the MER mission).

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Appendix A. Supplementary material

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References

[1] S.W. Squyres, et al., Athena Mars rover science investigation, J. Geophys. Res. 3 (2003) 806, http://dx.doi.org/10.1029/2003JE002121.
[2] R.E. Arvidson, S.W. Squyres, E.T. Baumgartner, P.S. Schenker, C.S. Niebur, K.W. Larsen, F.P. Seelos IV, N.O. Snider, B.L. Jolliff, FIDO prototype Mars rover field trials, Black Rock Summit, Nevada, as test of the ability of robotic mobility systems to conduct field science, J. Geophys. Res. ;107http://dx.doi.org/10.1029/2000JE001464. (FIDO 2-1–FIDO 2-16).
[3] P.G. Backes, J.S. Norris, M.W. Powell, M.A. Vona, R. Steinke, J. Wick, The Science Activity Planner for the Mars Exploration Rover mission: FIDO field test results, IEEEAC paper #1415, 2003.
[4] D.S. Bass, R.C. Wales, V.L. Shalin, Choosing Mars time: analysis of the Mars Exploration Rover experience, in: Proceedings of IEEE Aerospace Conference, 2005, p. 1162, doi: 10.1109/AERO.2005.1559722.
[5] J.P. Grotzinger, J. Crisp, A.R. Vasavada, R.C. Anderson, C.J. Baker, R. Barry, D.F. Blake, P. Conrad, K.S. Edgett, B. Ferdowski, R. Gellert, J.B. Gilbert, M. Golombek, J. Gómez-Elvira, D.M. Hassler, L. Jandura, M. Litvak, P. Mahaffy, J. Maki, M. Meyer, M.C. Malin, I. Mitrofanov, J.J. Simmonds, D. Vaniman, R.V. Welch, R.C. Wiens, Mars Science Laboratory mission and science investigation, Space Sci. Rev. 170 (2012) 5–56.
[6] M.G. Bualat, A. Abercromby, M. Allan, X. Bouyssounouse, M.C. Deans, T. Fong, L. Flückiger, K.V. Hodges, J. Hurtado Jr., L. Keely, L. Kobayashi, R. Landis, S.Y. Lee, P.C. Lee, D. Lees, E. Pacis, E. Park, L. Pedersen, D. Schreckenghost, T. Smith, V. To, H. Utz, Robotic recon for human exploration: method, assessment, and lessons learned, Geological Society of America Special Paper, Analogs for Planetary Exploration, 2010.
[7] M. Deans, T. Fong, M. Allan, X. Bouyssounouse, M. Bualat, L. Flueckiger, L. Kobayashi, S. Lee, D. Lees, E. Park, E. Pacis, L. Pedersen, D. Schreckenghost, T. Smith, V. To, H. Utz, Robotic scouting for human exploration, in: Proceedings of AIAA SPACE Conference, #6781, 2009.
[8] T. Fong, A. Abercromby, M.G. Bualat, M.C. Deans, K.V. Hodges, J. Hurtado Jr., R. Landis, P. Lee, D. Schreckenghost, Assessment of robotic recon for human exploration of the Moon, Acta Astronaut. 67 (2010) 9–10.
[9] B.L. Jolliff, J.J. Gillis, L.A. Haskin, R.L. Korotev, M.A. Wieczorek, Major lunar crustal terranes: surface expressions and crust-mantle origins, J. Geophys. Res. 105 (2000) 4197–4216.
[10] Exploration Systems Architecture Study (ESAS), NASA Final Report, 2005.
[11] National Research Council, The Scientific Context for Exploration of the Moon, National Academies Press, New York, NY, 2007.
[12] B.G. Drake, Human Exploration of Mars Design Reference Architecture 5.0, NASA-SP-2009-566, July 2009.
[13] B. Glass, et al. (2006) LPS XXXVII, 2300, in: B. Glass, H. Cannon, S. Hanagud, P. Lee, G. Paulsen (Eds.), Proceedings of the 37th Lunar Planetary Science Conference on Drilling Automation Tests at a Lunar/Mars Analog Site, 2006, p. 2300.
[14] R. Greeley, A.T. Basilevsky, R.O. Kuzmin, C.R. Stoker, G.J. Taylor, Science results from the Marsokhod tests, Amboy lava field, California, Paper presented at the International Planetary Rover Symposium, Moscow, Russia, May 1994.
[15] P. Lee, et al. Haughton-Mars Project: 10 years of science operations and exploration systems development at a Moon/Mars analog site on Devon Island, High Arctic, in: Proceedings of the 38th Lunar Planetary Science Conference, 2007, p. 2426.
[16] M.J. Roman, D.P. Miller, Experiments with a More Capable Lunar Rover, Abstracts of the 6th International Lunar Conference, Udaipur, India, 2004.

[17] C. Stoker, B. Hine, Telepresence control of mobile robots: Kilauea Marsokhod experiment, Paper 96-0338, American Institute of Aeronautics and Astronautics, Reno, NV, 1996.
[18] C. Stoker, The search for life on Mars: the role of rovers, J. Geophys. Res. 103 (1998) 28,557–28,575.
[19] G.J. Taylor, J. Aubele, C. Coombs, L. Crumpler, G. Ryder, Kilauea Marsokhod experiment: Lunar team report (1995), NASA Ames Reserch Center, Mountain View, CA, 1995.
[20] W. Whittaker, D. Bapna, M.W. Maimone, E. Rollins, Atacama Desert trek: a planetary analog field experiment, in: Proceedings of the 7th International Symposium on Artificial Intelligence, Robotics, and Automation for Space, Tokyo, Japan, 1997.
[21] R.A. Yingst, B.A. Cohen, L. Crumpler, M.E. Schmidt, C.M. Schrader, Testing Mars-inspired operations strategies for semi-autonomous rovers on the Moon: the GeoHeuristic Operational Strategies Test in New Mexico, Mars 6 (2011) 13–31.
[22] J. Papike, L. Taylor, S. Simon, Lunar minerals, in: G.H. Heiken, D.T. Vaniman, B.M. French (Eds.), Lunar Sourcebook, Cambridge University Press, Cambridge, England, 1991, pp. 121–181.
[23] F.M. McCubbin, H. Nekvasil, Maskelynite-hosted apatite in the Chassigny meteorite: insights into late-stage magmatic volatile evolution in martian magmas, Am. Mineral. 93 (2008) 676–684.
[24] A.E. Saal, E.H. Hauri, M. Lo Cascio, J.A. Van Orman, M.C. Rutherford, R.F. Cooper, Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior, Nature 454 (2008) 192–195, http://dx.doi.org/10.1038/nature07047.
[25] P.G. Lucey, A lunar waterworld, Science 326 (2009) 531–532.
[26] R.N. Clark, Detection of adsorbed water and hydroxyl on the Moon, Science 326 (2009) 562–564, http://dx.doi.org/10.1126/science.1178105.
[27] C.M. Pieters, J.N. Goswami, R.N. Clark, M. Annadurai, J. boardman, B. Buratti, J.-P. Combe, M.D. Dyar, R. Green, J.W. Head, C. Hibbitts, M. Hicks, P. Isaacson, R. Klima, G. Kramer, S. Kumar, E. Livo, S. Mundeen, E. Malaret, T. McCord, J. Mustard, J. Nettles, N. Petro, C. Runyon, M. Staid, J. Sunshine, L.A. Taylor, S. Tompkins, P. Varanasi, Character and spatial distribution of OH/H_2O on the surface of the Moon seen by M3 on Chandrayaan-1, Science 326 (2009) 568–572.
[28] J.M. Sunshine, T.L. Farnham, L.M. Feaga, O. Groussin, F. Merlin, R.E. Milliken, M.F. A'Hearn, Temporal and spatial variability of lunar hydration as observed by the Deep Impact spacecraft, Science 326 (2009) 565–568.
[29] D.A. Paige, M.A. Siegler, J. Zhang, P.O. Hayne, E.J. Foote, K.A. Bennett, A.R. Vasavada, B.T. Greenhagen, J.T. Schofield, D.J. McCleese, M.C. Foote, E. DeJong, B.G. Bills, W. Hartford, B.C. Murray, C.C. Allen, K. Snook, L.A. Soderblom, S. Calcutt, F.W. Taylor, N.E. Bowles, J.L. Bandfield, R. Elphic, R. Ghent, T.D. Glotch, M.B. Wyatt, P.G. Lucey, Diviner lunar radiometer observations of cold traps in the Moon's south polar region, Science 330 (2010) 479–482.
[30] J. Haruyama, M. Ohtake, T. Matsunaga, T. Morota, C. Honda, Y. Yokota, C.M. Pieters, S. Hara, K. Hioki, K. Saiki, H. Miyamoto, A. Iwasaki, M. Abe, Y. Ogawa, H. Takeda, M. Shirao, A. Yamaji, J. –L. Josset, Lack of exposed ice inside Lunar South Pole Shackleton Crater, Science 322 (2008) 938–939.
[31] P.D. Spudis, D.B.J. Bussey, S.M. Baloga, B.J. Butler, D. Cari, L.M. Carter, M. Chakraborty, R.C. Elphic, J.J. Gillis-Davis, J.N. Goswami, E. Heggy, M. Hillyard, R. Jensen, R.L. Kirk, D. LaVallee, P. McKerracher, C.D. Neish, S. Nozette, S. Nylund, M. Palsetia, W. Patterson, M.S. Robinson, R.K. Raney, R.C. Schulze, H. Sequeira, J. Skura, T.W. Thompson, B.J. Thomson, E.A. Ustinov, H.L. Winters, Initial results for the north pole of the Moon from Mini-SAR, Chandrayaan-1 mission, Geophys. Res. Lett. 37 (2010) 06204.
[32] R.A. Kerr, Cheapest mission finds Moon's frozen water, Science 279 (1998) 1628, http://dx.doi.org/10.1126/science.279.5357.1628a.
[33] R.A. Kerr, Yes, there's ice on the Moon—but how much and what use is it? Science 326 (2009) 1046, http://dx.doi.org/10.1126/science.326.5956.1046-a.
[34] W.C. Feldman, S. Maurice, D.J. Lawrence, R.C. Little, S.L. Lawson, O. Gasnault, R.C. Wiens, B.L. Barraclough, R.C. Elphic, T.H. Prettyman, J.T. Steinberg, A.B. Binder, Evidence for water ice near the lunar poles, J. Geophys. Res. 106 (2012) 23,231–23,251, http://dx.doi.org/10.1029/2000JE001444.
[35] D.J. Lawrence, W.C. Feldman, R.C. Elphic, J.J. Hagerty, S. Maurice, G.W. McKinney, T.H. Prettyman, Improved modeling of Lunar Prospector neutron spectrometer data: implications for hydrogen deposits at the lunar poles, J. Geophys. Res. 111 (2006) E08001, http://dx.doi.org/10.1029/2005JE002637.
[36] R.S. March, S. O'Neel, Gulkana Glacier, Alaska – Mass Balance, Meteorology, and Water Measurements, 1997–2001, USGS Scientific Investigations Report, 2011, pp. 2011–5046.
[37] T.L. Péwé, R.D. Reger, Delta River area, Alaska Range, in: T.L. Péwé, R.D. Reger (Eds.), Guidebook to Permafrost and Quaternary Geology Along the Richardson and Glenn Highways Between Fairbanks and Anchorage, Fourth International Conference on Permafrost: Alaska Division of Geological and Geophysical Surveys—Guidebook, vol. 1, Alaska, 1983, pp. 47–135.
[38] G.C. Bond, Geology of the Rainbow Mountain-Gulkana Glacier Area, Eastern Alaska Range, with Emphasis on Upper Paleozoic Strata, Alaska Division of Geological and Geophysical Surveys Geologic Report 45, 1976, 47 pp.
[39] W.J. Nokleberg, J.N. Aleinikoff, L.M. Lange, S.R. Silva, R.T. Miyaoka, C.E. Schwab, R.E. Zehner, Preliminary Geologic Map of the Mount Hayes Quadrangle, Eastern Alaska Range, U.S. Geological Survey Open-File Report 92-594, Scale 1:250,000, Alaska, 1992.
[40] D.E. Lawson, Overview of the Matanuska Glacier, in: T.L. Péwé, R.D. Reger (Eds.), Guidebook to Permafrost and Quaternary Geology Along the Richardson and Glenn Highways Between Fairbanks and Anchorage, Fourth International Conference on Permafrost: Alaska Division of Geological and Geophysical Surveys—Guidebook 1, Alaska, 1983, pp. 47–135.
[41] G.R. Winkler, Geologic Map and Summary Geochronology of the Anchorage $1^\circ \times 3^\circ$ Quadrangle, Southern Alaska, Miscellaneous Investigations Series, U.S. Geological Survey Map I-2283, Scale 1:250,000, 1992.
[42] G. Plafker, D.L. Jones, E.A. Pessagno Jr., A Cretaceous accretionary flysch and mélange terrane along the Gulf of Alaska margin, in: K.M. Blean (Ed.), The United States Geological Survey in Alaska – Accomplishments During 1976, The U.S. Geological Survey Circular 751-B, 1977, pp. B41–B43.
[43] L.E. Burns, The Border Ranges ultramafic and mafic complex, south-central Alaska – cumulate fractionates of island-arc volcanics, Can. J. Earth Sci. 22 (1985) 1020–1038.
[44] J.F. Bell III, S.W. Squyres, K.E. Herkenhoff, J.N. Maki, H.M. Ameson, D. Brown, S.A. Collins, A. Dingizian, S.T. Elliot, E.C. Hagerott, A.G. Hayes, M.J. Johnson, J.R. Johnson, J. Joseph, K. Kinch, M.T. Lemmon, R.V. Morris, L. Scherr, M. Schwochert, M.K. Shepard, G.H. Smith, J.N. Sohl-Dickstein, R.J. Sullivan, W.T. Sullivan, M. Wadsworth, Mars Exploration Rover Athena Panoramic Camera (Pancam) investigation, J. Geophys. Res.108; http://dx.doi.org/10.1029/2003JE002070.
[45] J.N. Maki, J.F. Bill III, K.E. Herkenhoff, S.W. Squyres, A. Kiely, M. Klimesh, M. Schwochert, T. Litwin, R. Wilson, A. Johnson, M. Maimone, E. Baumgartner, A. Collins, M. Wadsworth, S.T. Elliot, A. Dingizian, D. Brown, E.C. Hagerott, L. Scherr, R. Deen, D. Alexander, J. Lorre, Mars Exploration Rover engineering cameras, J. Geophys. Res.108; http://dx.doi.org/10.1029/2003JE002077.
[46] K. Herkenhoff, et al., Athena Microscopic Imager investigation, J. Geophys. Res. ;108http://dx.doi.org/10.1029/2003JE002076.
[47] P.R. Christensen, G.L. Mehall, S.H. Silverman, S. Anwar, G. Cannon, N. Gorelick, R. Kheen, T. Tourville, D. Bates, S. Ferry, T. Fortuna, J. Jeffryes, W. O'Donnell, R. Peralta, T. Wolverton, D. Blaney, R. Denise, J. Rademacher, R.V. Morris, S. Squyres, Miniature thermal emission spectrometer for the Mars Exploration Rovers, J. Geophys. Res.108; http://dx.doi.org/10.1029/2003JE002117.
[48] G. Klingelhöfer, R.V. Morris, B. Bernhardt, D. Rodionov, P.A. de Souza Jr., S.W. Squyres, J. Foh, E. Kankeleit, U. Bonnes, R. Gellert, C. Schröder, S. Linkin, E. Evlanov, B. Zubkov, O. Prilutski, Athena MIMOS II Mössbauer spectrometer, investigation, J. Geophys. Res.108; (2003) 8067, http://dx.doi.org/10.1029/2003JE002138.
[49] R. Rieder, R. Gellert, J. Brückner, G. Klingelhöfer, G. Dreibus, A. Yen, S.W. Squyres, The new Athena alpha particle X-ray spectrometer for the Mars Exploration Rover, J. Geophys. Res. 108 (2003) 8066, http://dx.doi.org/10.1029/2003JE002150.
[50] K.S. Edgett, R.A. Yingst, M.A. Ravine, M.A. Caplinger, J.N. Maki, F.T. Ghaemi, J.A. Schaffner, J.F. Bell III, L.J. Edwards, K.E. Herkenhoff, E. Heydari, L.C. Kah, M.T. Lemmon, M.E. Minitti, T.S. Olson, T.J. Parker, S.K. Rowland, J. Schieber, R.J. Sullivan, D.Y. Sumner, P.C. Thomas, E.H. Jensen, J.J. Simmonds, A.J. Sengstacken, R.G. Willson, W. Goetz, Curiosity's Mars Hand Lens Imager (MAHLI) Investigation, Space Sci. Rev. 170 (1–4) (2012) 259–317, http://dx.doi.org/10.1007/s11214-012-9910-4.
[51] J.P. Grotzinger, et al., Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars, Earth Planet. Sci. Lett. 240 (2005) 11–72.
[52] S.W. Squyres, A.H. Knoll, R.E. Arvidson, B.C. Clark, J.P. Grotzinger, B.L. Joliff, S.M. McLennan, N. Tosca, J.F. Bell III, W.M. Calvin, W.H. Farrand, T.D. Glotch, M.P. Golombek, K.E. Herkenhoff, J.R. Johnson, G. Klingelhöfer, H.Y. McSween, A.S. Yen, Two years at Meridiani Planum: results from the Opportunity Rover, Science 313 (2006) 1403–1407, http://dx.doi.org/10.1126/science.1130890.

[53] S.W. Squyres, R.E. Arvidson, J.F. Bell III, F. Calef III, B.C. Clark, B.A. Cohen, L.A. Crumpler, P.A. de Souza Jr., W.H. Farrand, R. Gellert, J. Grant, K.E. Herkenhoff, J.A. Hurowitz, J.R. Johnson, B.L. Jolliff, A.H. Knoll, R. Li, S.M. McLennan, D.W. Ming, D.W. Mittlefehldt, T.J. Parker, G. Paulsen, M.S. Rice, S.W. Ruff, C. Schröder, A.S. Yen, K. Zacny, Ancient impact and aqueous processes at Endeavour Crater, Mars, Science 336 (2012) 570–576, http://dx.doi.org/10.1126/science.1220476.

[54] R.A. Yingst, L.C. Kah, M. Palucis, R.M.E. Williams, J. Garvin, J.C. Bridges, N. Bridges, R.G. Deen, J. Farmer, O. Gasnault, W. Goetz, V.E. Hamilton, V. Hipkin, J.K. Jensen, P.L. King, A. Koefoed, S. Maurice, E.M. McCartney, H. Newsom, O. Pariser, V.H. Sautter, R.C. Wiens, Characteristics of pebble- and cobble-sized clasts along the Curiosity rover traverse from Bradbury Landing to Rocknest, J. Geophys. Res., 118 (2013) 2361–2380, http://dx.doi.org/10.1002/2013JE004435.

[55] B.A. Cohen, B.C. Clark, G. Klingelhöfer, D.W. Ming, D.W. Mittlefehldt, R.V. Morris, C.M. Schrader, C. Schröder, A.S. Yen, T. Economou, P. DeSouza, B.L. Joliff, R.E. Arvidson, S.W. Squyres, Mars Exploration Rover APXS results from Matejevic Hill, in: Proceedings of the 44th Lunar Planetary Science Conference, 2013, #2294.

[56] I. Antonenko, G.R. Osinski, M. Battler, M. Beauchamp, L. Cupelli, A. Chanou, R. Francis, M.M. Mader, C. Marion, E. McCullough, A.E. Pickersgill, L.J. Preston, B. Shankar, T. Unrau, D. Veillette, Issues of geologically-focused situational awareness in robotic planetary missions: lessons from an analogue mission at Mistastin Lake impact structure, Labrador, Canada, Adv. Space Res. 52 (2013) 272–284.

[57] D.B. Eppler, B. Adams, D. Archer, G. Baiden, A. Brown, W. Carey, B. Cohen, C. Condit, C. Evans, C. Fortezzo, b. Garry, T. Graff, J. Gruener, J. Heldmann, K. Hodges, F. Hörz, J. Hurtado, B. Hynek, P. Issacson, C. Juranek, K. Klaus, D. Kring, N. Lanza, S. Lederer, G. Lofgren, M. Marinova, L. May, J. Meyer, D. Ming, B. Monteleone, C. Morisset, S. Noble, E. Rampe, J. Rice, J. Schutt, J. Skinner, C.M. Tewksbury-Christle, B.J. Tewksbury, A. Vaughan, A. Yingst, K. Young, Desert Research and Technology Studies (DRATS) 2010 science operations: operational approaches and lessons learned for managing science during human planetary surface missions, Acta Astronaut. 90 (2013) 224–241.

[58] R.A. Yingst, et al., Comparing Apollo and Mars Exploration Rover (MER)/phoenix operations paradigms for human exploration during NASA Desert-RATS science operations, Acta Astronaut. 90 (2011) 311–317, http://dx.doi.org/10.1016/j.actaastro.2011.10.001.

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